

KESAN KADAR TERIKAN TERHADAP SIFAT-SIFAT TEGANGAN DAN  
PENENTUAN KELIATAN PATAH BAGI ALOI Mg-Al-Zn TERSEMPRIT

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### **DECLARATION**

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

6 October 2015

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## ABSTRACT

Extruded Mg-Al-Zn alloy is a lightweight and high strength magnesium alloy that is becoming a preferred material to be used as a structural component in automobiles. During a crash event, an automobile structure is subjected to dynamic loading. The magnesium alloy structures must be able to maintain its integrity and provide adequate protection in survivable crashes. Besides static tensile properties, tensile properties at high strain rates of extruded magnesium alloys and their fracture behaviour are some of the important parameters to be considered in design in ensuring the durability and reliability of automobile structures. In this study, the effect of strain rates on tensile properties and work hardening behaviour were evaluated for extruded Mg-Al-Zn alloys. Further, the fracture behaviour at different loading rates and the effect of temperature on fracture toughness of Mg-Al-Zn alloys were investigated. The extruded Mg-Al-Zn alloys used in this study were AZ61 and AZ31 magnesium alloys. Tensile tests under low and high strain rates were carried out using a universal testing machine and high strain rate tensile tester, respectively. The high strain rate tensile tester was designed and fabricated in-house to fulfil the requirement of tensile test under high strain rate ranging from 100 to 600 s<sup>-1</sup>. Work hardening behaviour for low strain rate tensile specimen was determined by referring to the ASTM E646. To obtain the fracture behaviour of both alloys at different loading rates, three-point bending fracture test was conducted on pre-cracked specimens. Standard test methods i.e. ASTM E1820 and JSME S001 were referred to determine the elastic-plastic fracture toughness  $J_{IC}$  value of AZ31 and AZ61 alloys. The  $J_{IC}$  value obtained were then used as a standard reference value to identify a proper groove depth of a single side-grooved specimen. The side-groove depths evaluated were 25%, 35% and 50%. The proper depth of the side-grooves is confirmed after the  $J$  value obtained from the side-grooved specimen test method is identical to the  $J_{IC}$  value that of the standard test method. The side-grooved specimen with proper groove depth was then used to determine the  $J_{IC}$  value of AZ61 alloy at high temperature. From the results, the tensile strengths were gradually increased with increasing strain rates. However, at above 200 s<sup>-1</sup>, the tensile strength increased significantly to more than 600 to 800 MPa. In addition, the work hardening rate for AZ61 was found higher compared to that of AZ31. Both alloys exhibited significant elastic-plastic fracture behaviour at different loading rates. It was found that 50% side-grooves depth is appropriate enough to produce valid  $J_{IC}$  value using a single specimen. This finding is very useful especially in determining  $J_{IC}$  value in a condition where standard multiple specimen test method is difficult to be conducted such as in high temperature environment. The  $J_{IC}$  values of AZ31 and AZ61 at room temperature were 19 and 25 kJ/m<sup>2</sup>, respectively. Meanwhile, the  $J_{IC}$  value of AZ61 at 150 °C was found twice higher than the  $J_{IC}$  value at room temperature.



## KESAN KADAR TERIKAN TERHADAP SIFAT-SIFAT TEGANGAN DAN PENENTUAN KELIATAN PATAH BAGI ALOI Mg-Al-Zn TERSEMPRIT

### ABSTRAK

Aloi Mg-Al-Zn tersempurit merupakan aloi magnesium yang ringan dan berkekuatan tinggi yang makin menjadi bahan pilihan untuk digunakan sebagai komponen struktur dalam kenderaan. Semasa kemalangan, struktur kenderaan dikenakan dengan beban dinamik. Struktur daripada aloi magnesium mestilah berupaya dalam mengekalkan integriti dan memberi perlindungan yang secukupnya semasa kemalangan. Selain sifat-sifat tegangan statik, sifat-sifat tegangan pada kadar terikan yang tinggi aloi magnesium tersempurit dan sifat patahnya adalah parameter penting yang perlu dipertimbangkan dalam rekabentuk bagi memastikan ketahanan dan kebolehpercayaan pada struktur kenderaan. Dalam kajian ini, kesan kadar terikan terhadap sifat-sifat tegangan dan sifat pengerasan kerja telah dinilai bagi aloi Mg-Al-Zn tersempurit. Seterusnya, sifat patah pada kadar pembebanan berbeza dan kesan suhu terhadap keliatan patah bagi aloi Mg-Al-Zn telah dikaji. Aloi Mg-Al-Zn tersempurit yang digunakan dalam kajian ini adalah aloi magnesium AZ31 dan AZ61. Ujian tegangan pada kadar terikan rendah dan tinggi telah dijalankan dengan masing-masing menggunakan mesin ujian semesta dan mesin ujian kadar terikan tinggi. Mesin ujian kadar terikan tinggi telah direka dan dibangunkan sendiri untuk memenuhi keperluan ujian tegangan pada kadar terikan tinggi di antara 100 sehingga 600 s<sup>-1</sup>. Sifat pengerasan kerja untuk spesimen tegangan pada kadar terikan rendah telah ditentukan dengan merujuk kepada ASTM E646. Bagi memperoleh sifat patah kedua-dua aloi pada kadar pembebanan yang berbeza, ujian patah tiga-titik lenturan telah dijalankan pada spesimen pra-retak. Kaedah ujian piawai iatu ASTM E1820 dan JSME S001 telah dirujuk untuk menentukan nilai  $J_{IC}$  keliatan patah elastik-plastik bagi aloi AZ31 dan AZ61. Nilai  $J_{IC}$  yang diperolehi kemudiannya digunakan sebagai nilai rujukan piawai untuk mengenalpasti kedalaman alur yang wajar pada satu spesimen sisi beralur. Kedalaman sisi beralur yang dinilai adalah 25%, 35% dan 50%. Kedalaman wajar bagi sisi alur disahkan selepas nilai  $J$  yang diperolehi daripada kaedah ujian spesimen sisi beralur adalah sama dengan nilai  $J_{IC}$  daripada kaedah ujian piawai. Spesimen sisi beralur dengan kedalaman alur yang wajar kemudiannya digunakan untuk menentukan nilai  $J_{IC}$  bagi aloi AZ61 pada suhu tinggi. Daripada keputusan, kekuatan tegangan meningkat secara perlahan dengan peningkatan kadar terikan. Bagaimanapun, pada kadar melebihi 200 s<sup>-1</sup>, kekuatan tegangan meningkat dengan ketara melebihi dari 600 hingga 800 MPa. Di samping itu, kadar pengerasan kerja untuk AZ61 didapati tinggi berbanding AZ31. Kedua-dua aloi mempamerkan sifat patah elastik-plastik yang ketara pada kadar pembebanan yang berbeza. Didapati 50% kedalaman sisi alur adalah cukup sesuai untuk mendapatkan nilai  $J_{IC}$  yang sah menggunakan hanya satu spesimen. Penemuan ini amat berguna terutamanya bagi menentukan nilai  $J_{IC}$  dalam keadaan di mana kaedah ujian piawai berbilang spesimen adalah sukar untuk dilakukan seperti dalam persekitaran suhu yang tinggi. Nilai-nilai  $J_{IC}$  bagi AZ31 and AZ61 pada suhu bilik adalah masing-masing 19 dan 25 kJ/m<sup>2</sup>. Sementara itu, nilai  $J_{IC}$  bagi AZ61 pada 150 °C didapati dua kali lebih tinggi berbanding nilai  $J_{IC}$  pada suhu bilik.

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## NOMENCLATURE

### Symbols

$a$	crack length
$\Delta a$	crack growth
$\frac{da}{dN}$	fatigue crack growth rate
$A$	area
$A_o$	original cross section area of test specimen
$A_i$	final cross section area of test specimen
$A_T$	area of cross section at force
$A_{max}$	area under the curve up to maximum load ( $P_{max}$ ) point
$A_{specimen}$	actual area under the curve of testing specimen
$A_{total}$	total area under the curve of test
$A_{jig}$	area under the curve of testing jigs
$b$	remaining crack ligament
$B$	specimen thickness
$B_N$	net specimen thickness
$B_e$	effective thickness
$B_{e1}$	effective thickness 1
$B_{e2}$	effective thickness 2
$B_{e3}$	effective thickness 3
$\beta$	second phase
$d$	displacement
$d_l$	length of long diagonal
$d_s$	side-grooves depth

$ds$	increment of the countour path
$E$	Young's modulus
$F$	force
$f(\alpha)$	geometry factor
$g$	acceleration of gravity (9.81 m/s <sup>2</sup> )
$h$	drop weight height
$J$	$J$ -integral
$J_C$	critical $J$ -integral
$J_{IC}$	fracture toughness $J_{IC}$
$K$	stress intensity factor
$K_s$	strength coefficient
$K_Q$	critical stress intensity factor
$K_I$	mode I stress intensity factor
$K_{Id}$	dynamic fracture toughness
$K_{IC}$	fracture toughness $K_{IC}$
$\Delta K$	stress intensity factor range
$K_m$	mean stress intensity factor
$K_{min}$	minimum stress intensity factor
$K_{max}$	maximum stress intensity factor
$L_o$	original gage length
$L_f$	final gage length
$dL$	increment of elongation
$m$	mass
$Mg_{17}Al_{12}$	precipitation

$n$	strain hardening exponent
$P$	load
$P_Q$	critical load
$P_5$	load at intersection of 95% slope on load-displacement curve
$P_{max}$	maximum load
$P_y$	load point at 0.2% offset from the linear slope on load-displacement curve
$R$	stress ratio
$S$	span length
$\Delta s$	displacement of loading points
$T$	outward traction vector on $ds$
$u$	displacement vector at $ds$ , $x$ , $y$ , $z$ of the rectangular coordinates
$v$	impact velocity or high strain rate
$w$	loading work per unit volume
$W$	specimen width
$W_P$	work done
$Y$	geometry factor
$\varepsilon$	elongation
$\varepsilon_T$	true strain
$\varepsilon_e$	true elastic strain
$\varepsilon_p$	true plastic strain
$d\varepsilon_T$	increment of true plastic strain
$\sigma_y$	yield stress
$\sigma_{UTS}$	tensile strength

$\sigma_f$  flow stress

$\sigma_c$  critical stress

$\sigma_T$  true stress

$d\sigma_T$  increment of true stress

$\Gamma$  path of the integral around the crack tip

$T\left(\frac{\partial u}{\partial x}\right)ds$  work input rate from the stress filed into the area enclosed by  $\Gamma$



PTTA UTHM  
PERPUSTAKAAN TUNKU TUN AMINAH



## Abbreviations

HCP	hexagonal close packed
CRSS	critical resolved shear stress
UTM	universal testing machine
LVDT	linear variable differential transformer
MSDS	material safety data sheet
CT	compact tension
SENB	single edge notched bending
EDM	electrical discharge machining
ASTM	American society for testing and materials
JSME	Japan society of mechanical engineers
LEFM	linear elastic fracture mechanics
EPFM	elastic-plastic fracture mechanics
SEM	scanning electron microscope
SHPB	split Hopkinson pressure bar

## Chapter I

### INTRODUCTION

#### 1.1 RESEARCH BACKGROUND

Magnesium alloys have been attractive to engineers due to their lightweight and high specific strength properties as compared to aluminium and medium-strength steel alloys (Smith 1998). The specific strength of alloys is measured based on the strength to the weight ratio, while the lightweight property refers to the density of alloys. In this regard, magnesium alloys have been used in electric and electronic appliances as well as automotive applications. In automotive applications, these parameters are beneficial to reduce fuel consumption, enhance the energy efficiency of engines and reduce emissions. In addition, magnesium alloys are also excellent in machinability, castability, recyclability and high damping capacity. Hence, magnesium alloys attract the automobile manufacturers to use these alloys as components and structures for replacing the conventional materials such as steel, cast iron and aluminium (Gaines 1995; Mordike & Ebert 2001; Kainer 2003; Watarai 2006). Magnesium has been used since the 1930s in the Volkswagen (VW) Beetle. Nowadays, automobile manufacturers such as Volkswagen, Audi, DaimlerChrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Fiat, Hyundai, and Kia Motors Corporation generally use magnesium alloys as components and structures (Gupta & Sharon 2011). However, utilisation of magnesium alloys in automotive applications is still limited compared to that of conventional materials (Luo 2002).

The most popular magnesium alloys used as automobile components and structures are AZ (Mg-Al-Zn), AM (Mg-Al-Mn), ZK (Mg-Zn-Zr) and WE (Mg-Y-RE) series magnesium alloys. This is due to the best properties of magnesium alloys

for certain applications are governed by the combination of alloying element contents. In the present study, Mg-Al-Zn series magnesium alloys have been used. The main elemental contents of Mg-Al-Zn alloys are aluminium and zinc. These main elements are beneficial for enhancing the strength of alloys (Kainer 2003). In addition, Mg-Al-Zn alloys are characterised as low cost, a good strength and good ductility alloy. Due to its ductile property, Mg-Al-Zn alloys are easy to produce in the shape of extruded and simple forged products. Therefore, extruded and simple forged products of Mg-Al-Zn alloys are used as components and structures in automobile applications (Becker & Fischer 2004).

Mechanical properties are referred to when choosing a good potential material especially for application in automobile concerned with the safety parameter and quality assurance. Mechanical properties comprise hardness, tensile properties, flexural strength, fracture toughness etc. Excellent mechanical properties refer to the potential material related to the durability and reliability of materials. In the present study, the potential materials such as Mg-Al-Zn alloys are beneficial for use in automobile applications to prevent or reduce the impact of critical damage in the case of accident. Mg-Al-Zn alloys are also ductile material (Becker & Fischer 2004) beneficial in automobile applications to prevent or reduce the critical crashes due to high energy absorption capability. However, application of Mg-Al-Zn alloys in extreme conditions is believed to give influenced on the mechanical properties. In general, extreme conditions are referred to the condition such as high loading rate, impact loading response, elevated temperature conditions etc. Tensile strength is significantly strain rate dependent for many materials. At the same time, tensile strength is also temperature dependent for pure and magnesium alloys (Chino 2002; Feng et al. 2014; Kim & Chang 2011; Ulacia et al. 2011). In case of accident, a high loading rate with impact response is significantly applied to the vehicle. Elevated temperature is commonly subjected to automobile components and structures since the powertrain applications such as transmission cases are operated up to 175 °C, while the engine blocks and engine pistons up to 200 °C and 300 °C, respectively (Luo 2002; Luo 2004; Gupta & Sharon 2011). Therefore, engine surrounding temperatures

could rise up to more than 100 °C. Hence, knowing the effect of extreme conditions on mechanical properties is for Mg-Al-Zn alloys are important.

## 1.2 PROBLEM STATEMENT

As mentioned, magnesium alloys have several advantages when used as components and structures in automobile applications. However, the utilisation of magnesium alloys in automobile applications is still limited compared to that of conventional materials (Luo 2002). This is because the conventional used are of significantly high strength materials beneficial for reducing or preventing critical crashes during accidents. Consequently, studies in obtaining the mechanical properties of those materials are also widely reported (Mutoh 1987; Yi & Xiao-Wei 1988; Kobayashi et al. 1997; Zhang & Shi 1992; Kong et al 2011). Thus, many automotive manufacturers are still using conventional materials in automotive applications.

Several series magnesium alloys are used in automotive application. For example, car body parts, crankcase, seat frame and wheel are made from AZ31, AZ91, AM60 and ZK30 magnesium alloys, respectively (Fink 2003; Friedrich & Mordike 2006; Becker & Fischer 2003). Commonly, these components and structures are subjected to high and different velocities, impact loads and then critical crash during accident. Hence, mechanical properties of magnesium alloys under impact response are required to refer prior to applying the potential magnesium alloys in automotive applications. In addition, it is important to understand these impact fracture properties to understand the material response after being subjected to similar actual situations during accident. However, in previous studies, most mechanical properties are reported under testing at static response and fatigue loads in the case of vibration in service applications (Chamos et al. 2008; Somekawa et al. 2008; Khan et al. 2006). Moreover, these fracture properties are not appropriate for crash design and impact fracture properties are preferable.

For magnesium alloys, mechanical properties of these alloys such as hardness and tensile properties are well known. In previous studies, many researchers reported

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